

(12) UK Patent

(19) GB

(11) 2 415 215

(13) B

(45) Date of publication: 23.05.2007

(54) Title of the invention: Lubrication system for radially expanding tubular members

(51) INT CL: E21B 43/10 (2006.01)

(21) Application No: 0517448.7

(22) Date of Filing: 26.01.2004

(30) Priority Data:

(31) 60442938 (32) 27.01.2003 (33) US

(60) Parent of Application No(s)

0701860.9, 0614415.8 under Section 15(4) of the Patents Act 1977

(86) International Application Data:

PCT/US2004/002122 En 26.01.2004

(87) International Publication Data:

WO2004/067961 En 12.08.2004

(43) Date A Publication:

21.12.2005

(52) UK CL (Edition X):

E1F FLA

(56) Documents Cited:

GB 2410280 A

GB 2365898 A

GB 2347952 A

WO 2001/026860 A1

JP 2001047161 A

US 6568471 B1

US 6557640 B1

(58) Field of Search:

As for published application 2415215 A viz:

INT CL<sup>7</sup> E21B

Other

EAST

updated as appropriate

(72) Inventor(s):

Mark Shuster

Kevin Karl Waddell

Larry Kendziora

Scott Costa

(73) Proprietor(s):

Enventure Global Technology

(Incorporated in USA - Delaware)

16200-A Park Row, Houston, Texas 77084,

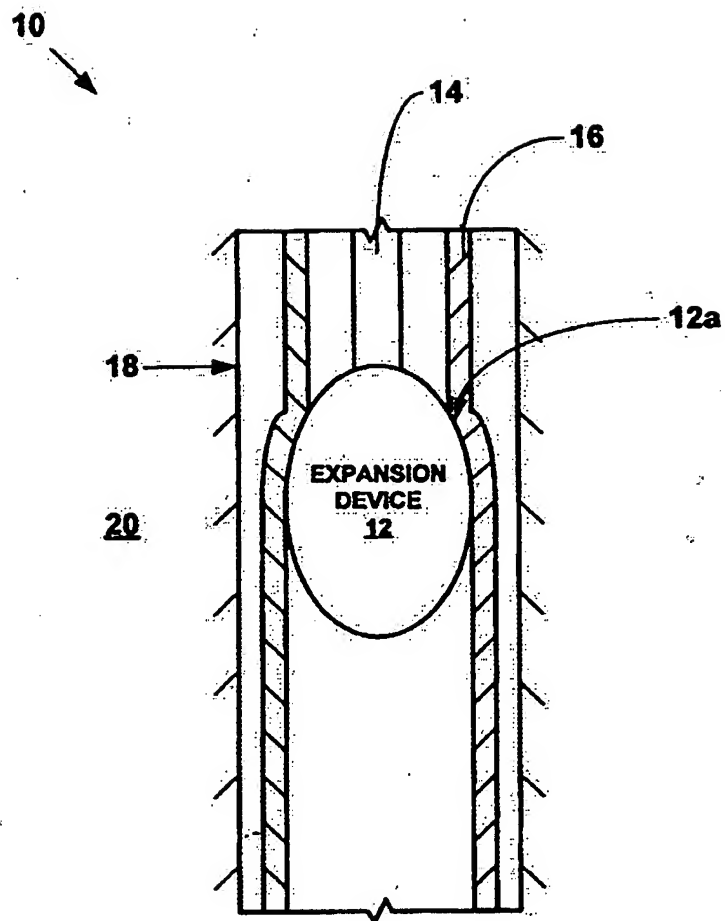
United States of America

(74) Agent and/or Address for Service:

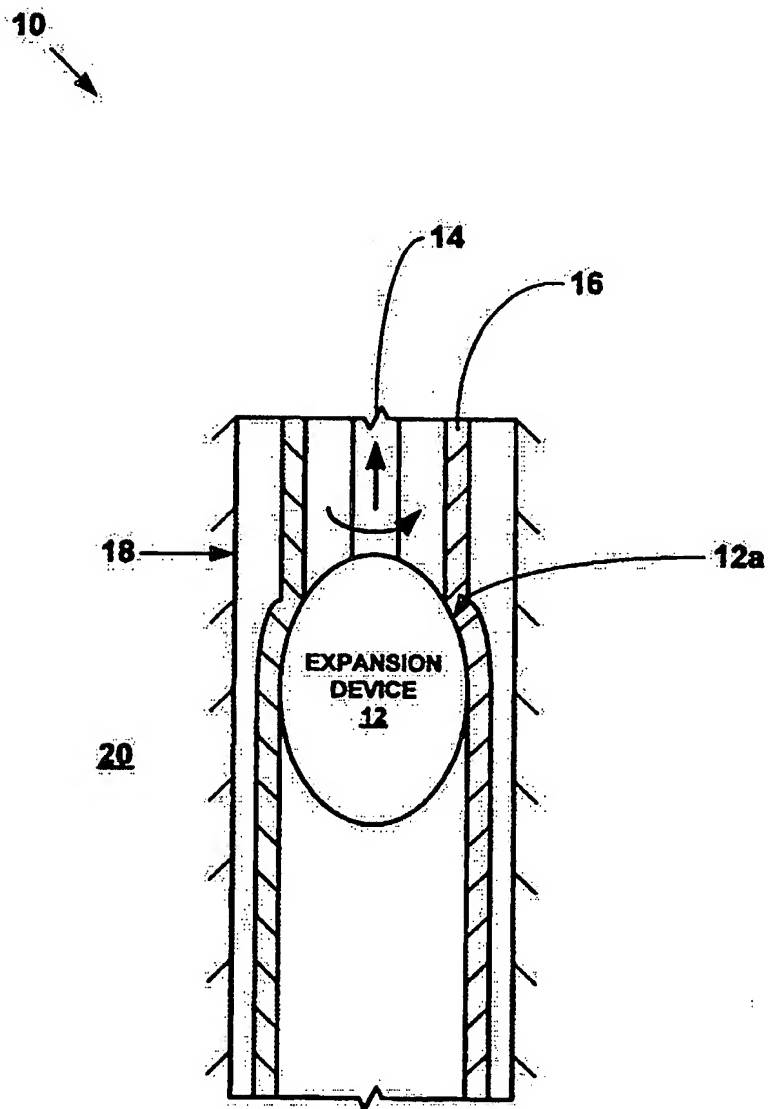
Haseltine Lake

Redcliff Quay, 120 Redcliff Street, Bristol,

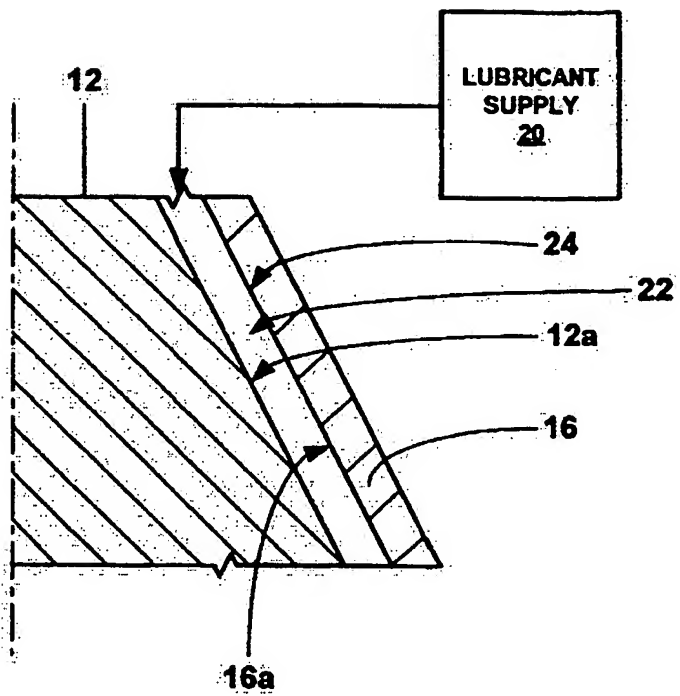
BS1 6HU, United Kingdom



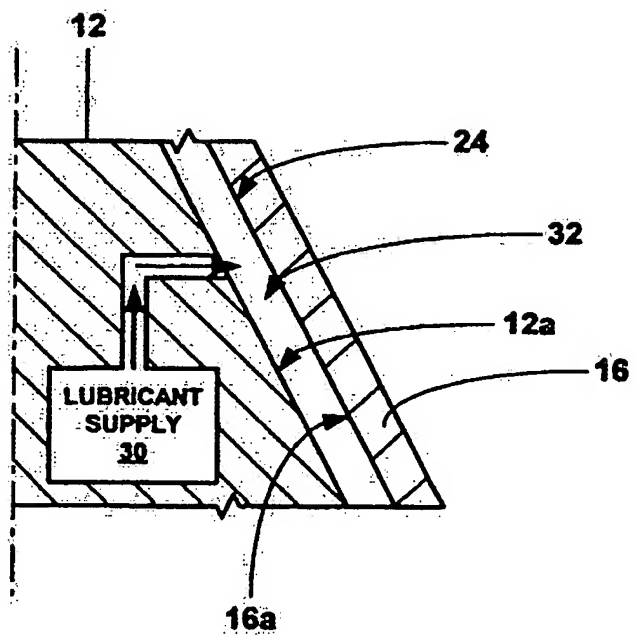
**Fig. 1a**



**Fig. 1b**

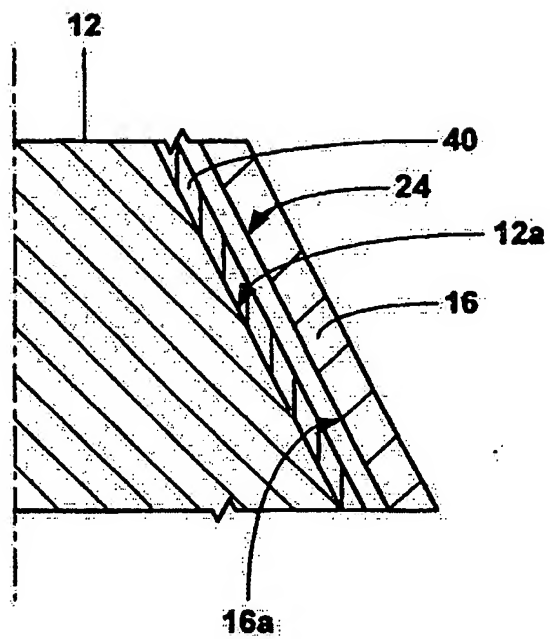


**Fig. 2**

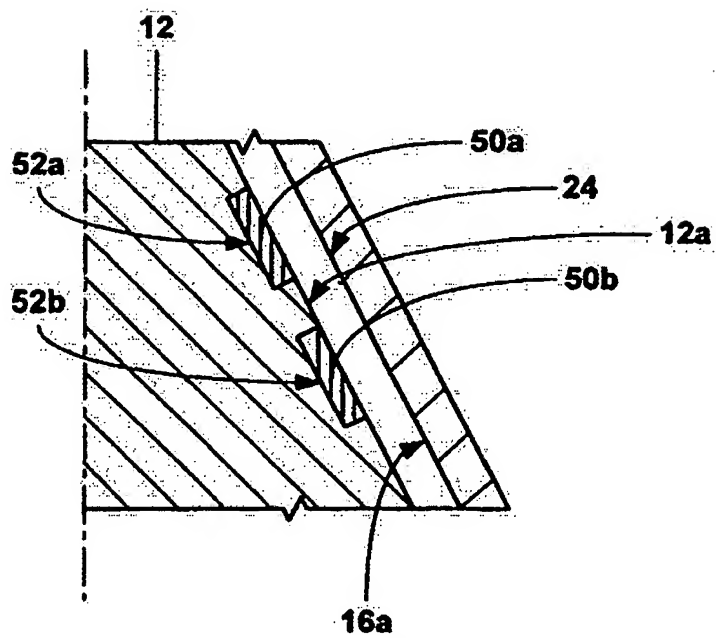


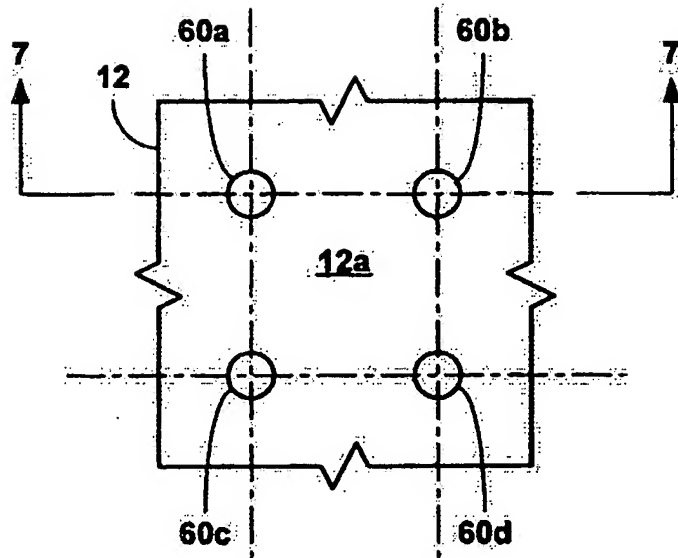
**Fig. 3**

**Fig. 4**

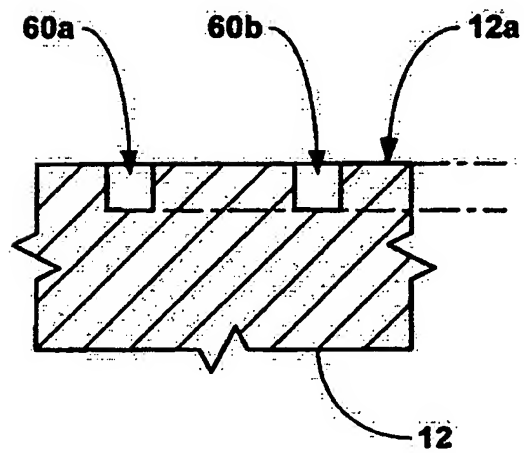


**Fig. 5**

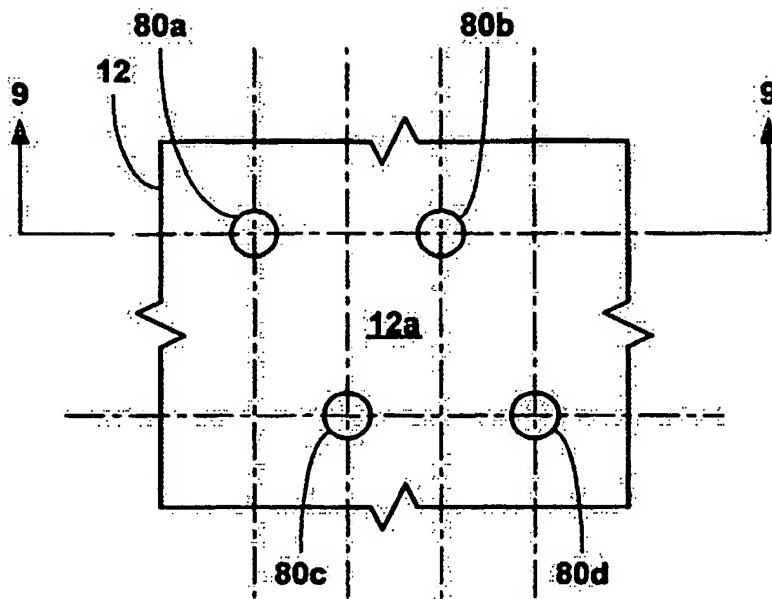




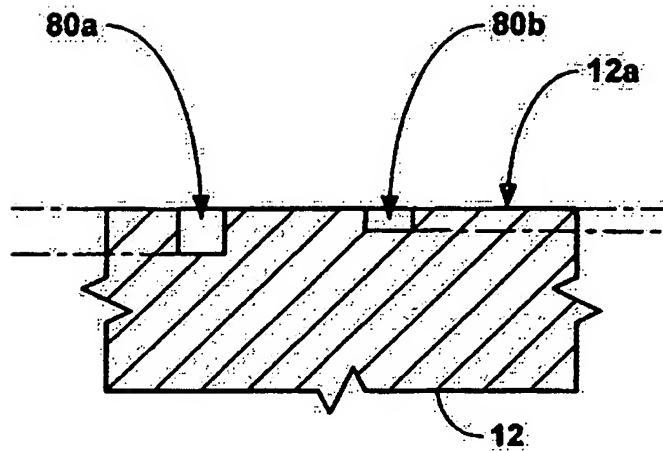
**Fig. 6**



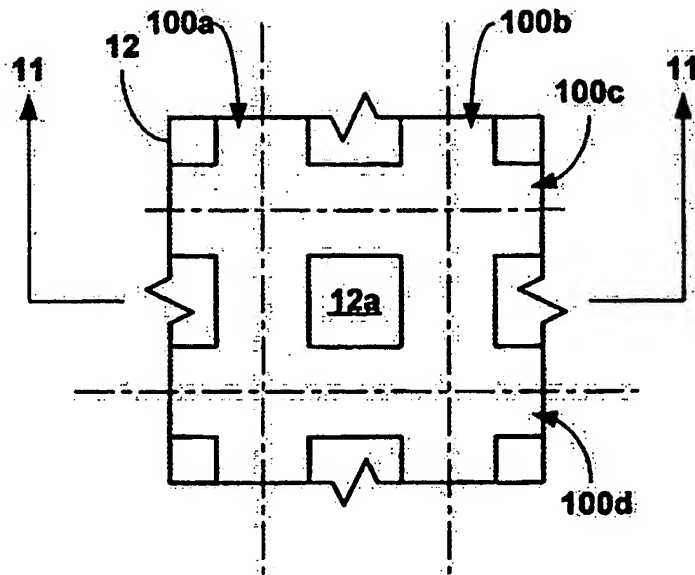
**Fig. 7**



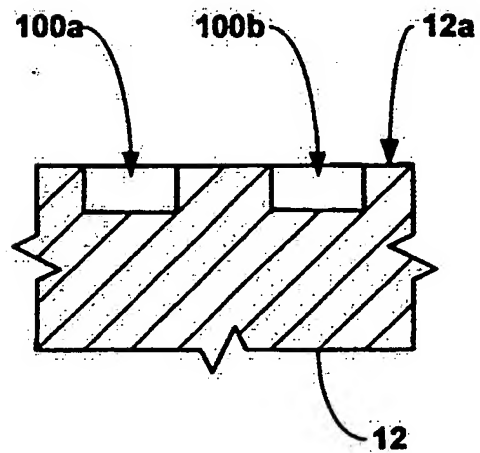
**Fig. 8**



**Fig. 9**

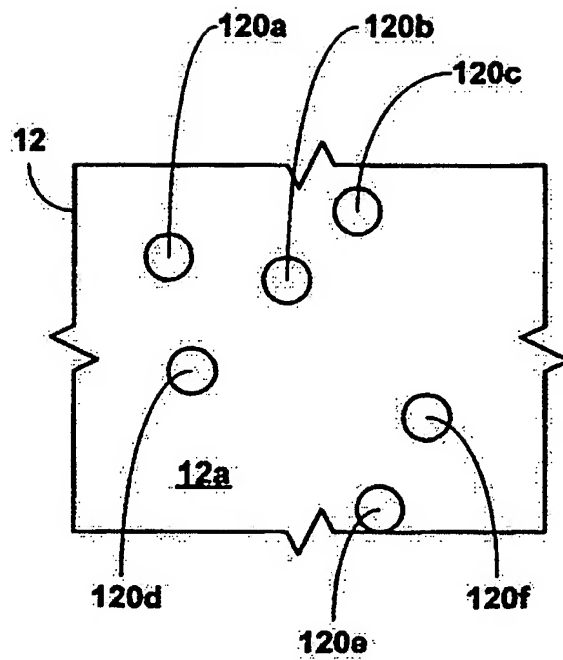


**Fig. 10**

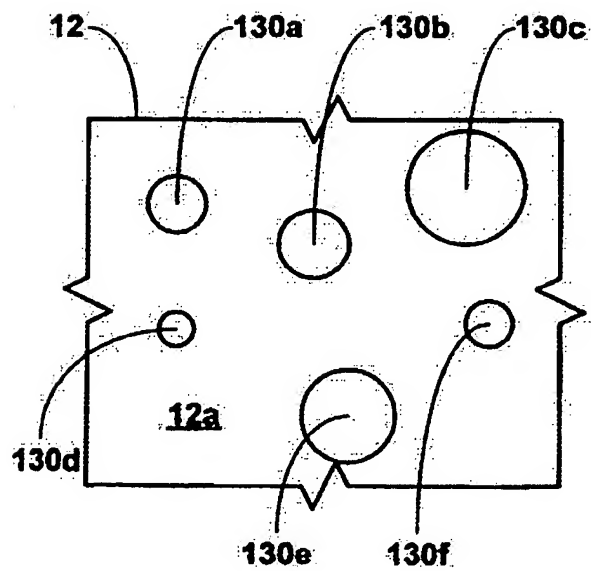


**Fig. 11**

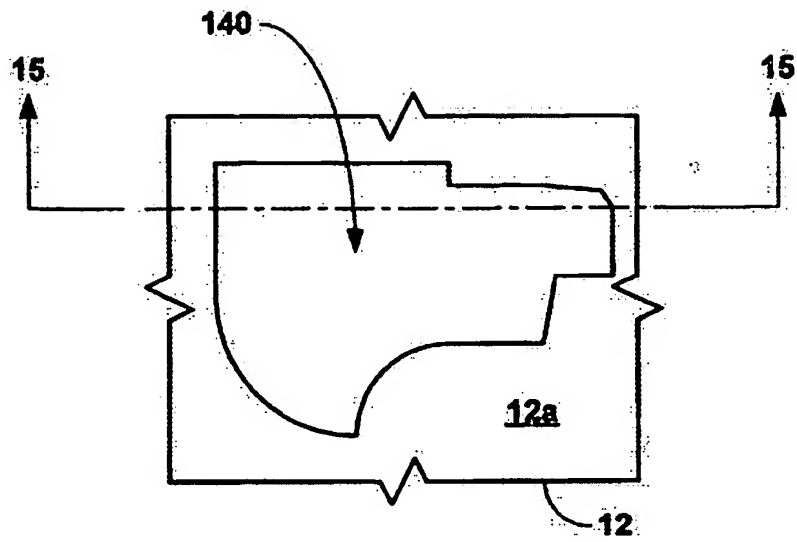




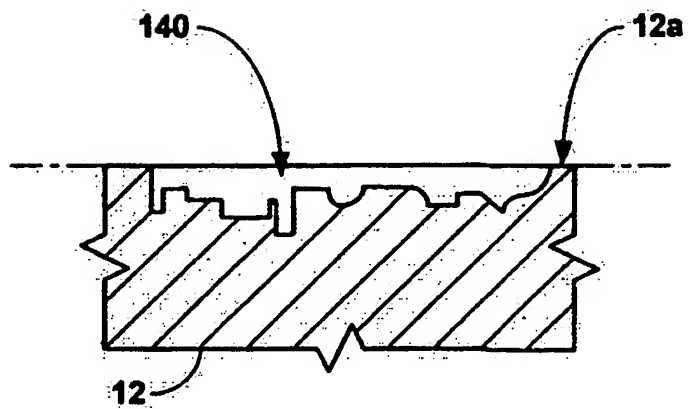
**Fig. 12**



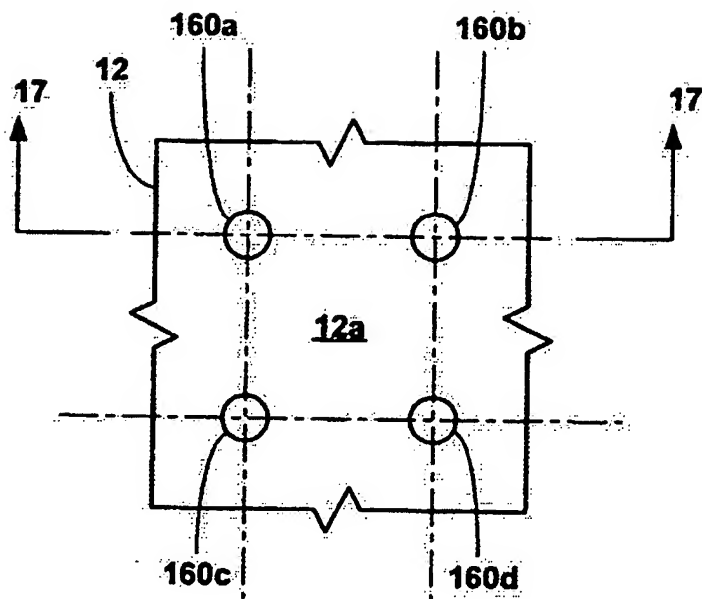
**Fig. 13**



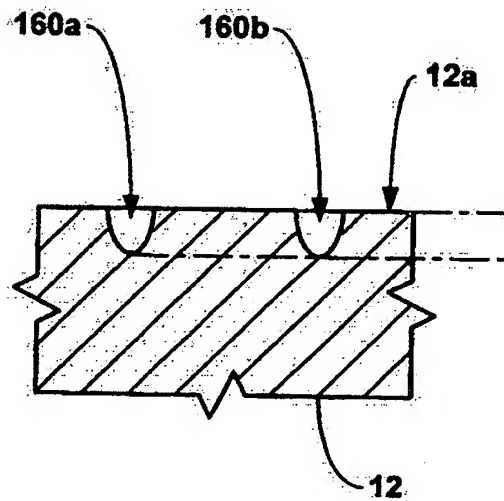
**Fig. 14**



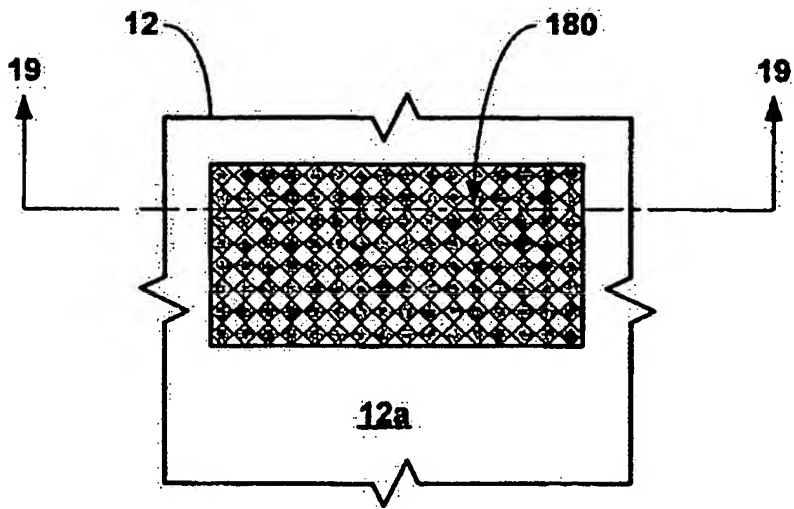
**Fig. 15**



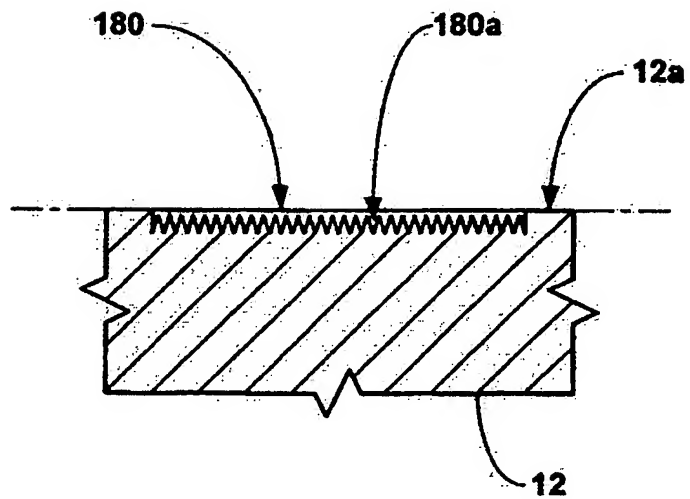
**Fig. 16**



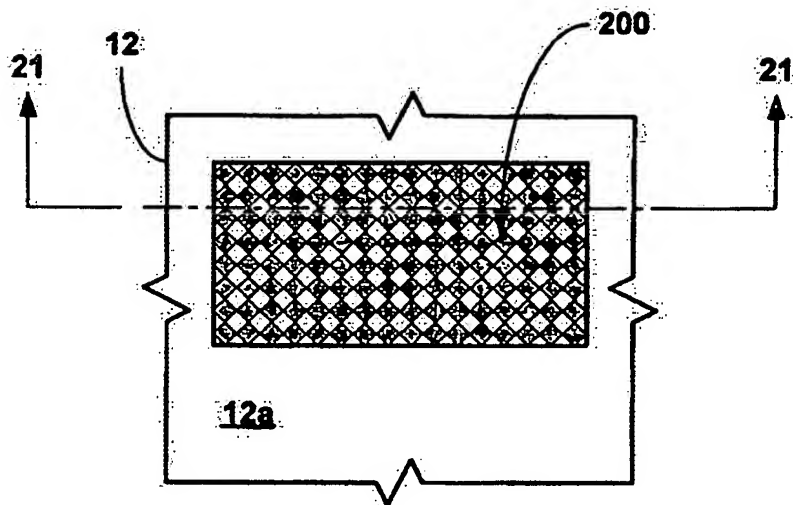
**Fig. 17**



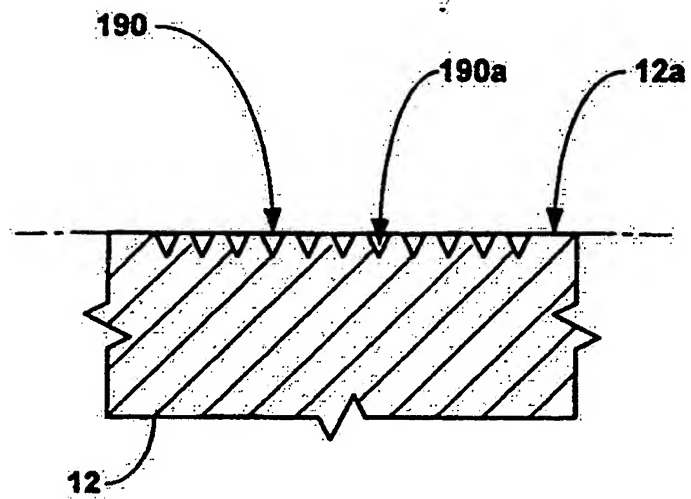
**Fig. 18**



**Fig. 19**



**Fig. 20**



**Fig. 21**

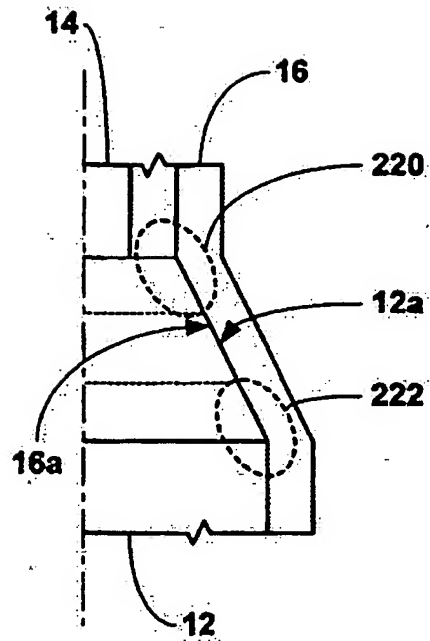


Fig. 22

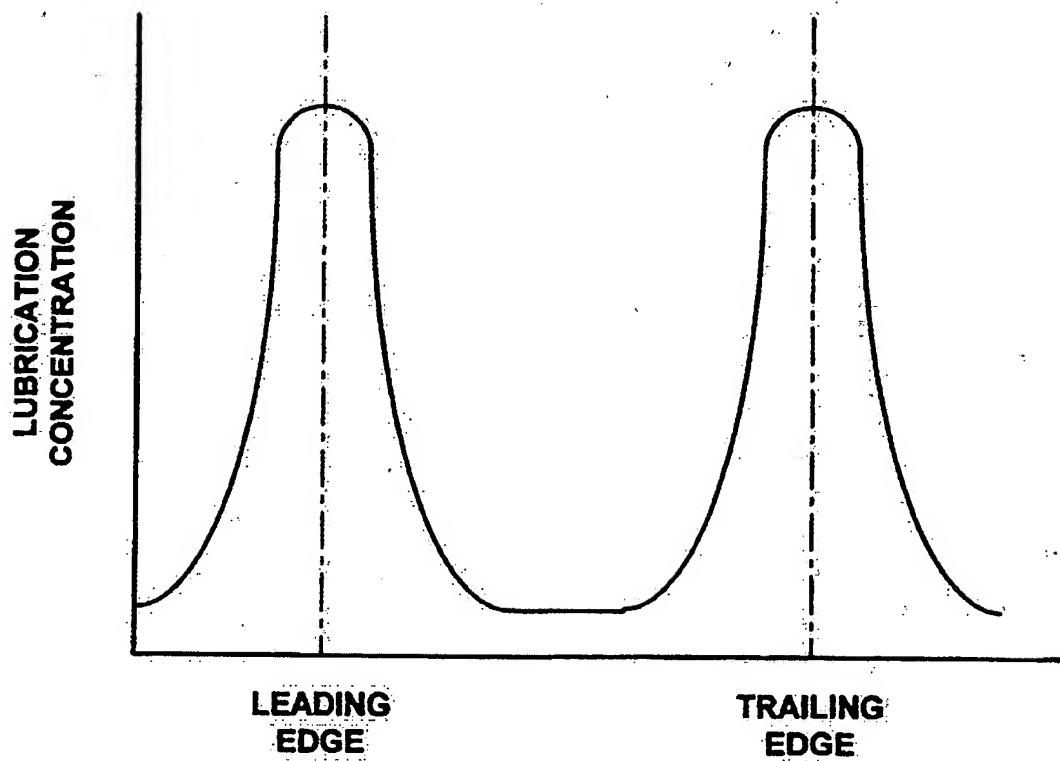
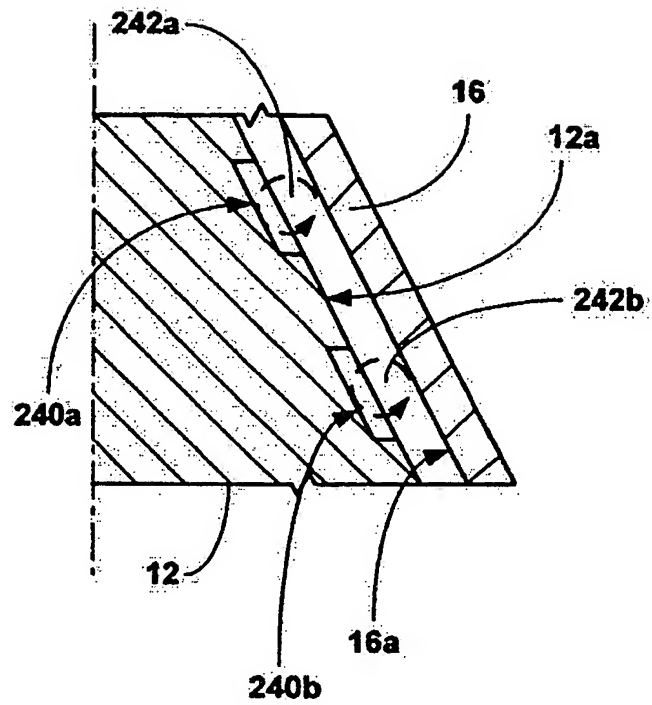
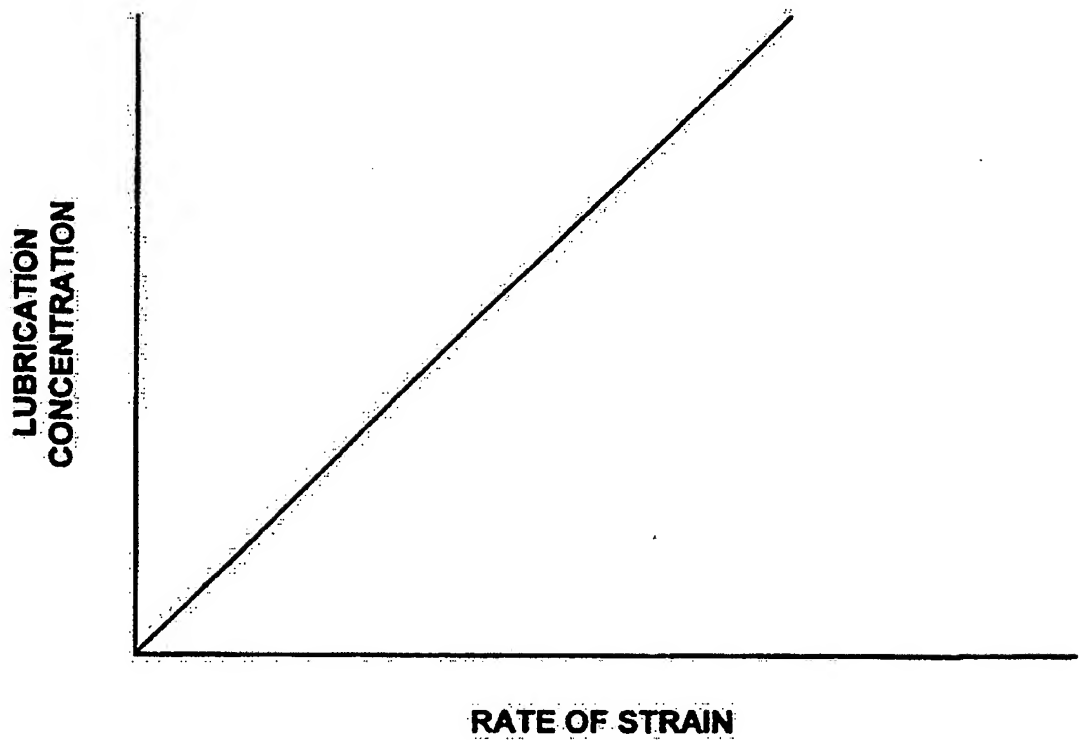


Fig. 23



**Fig. 24**



**Fig. 25**

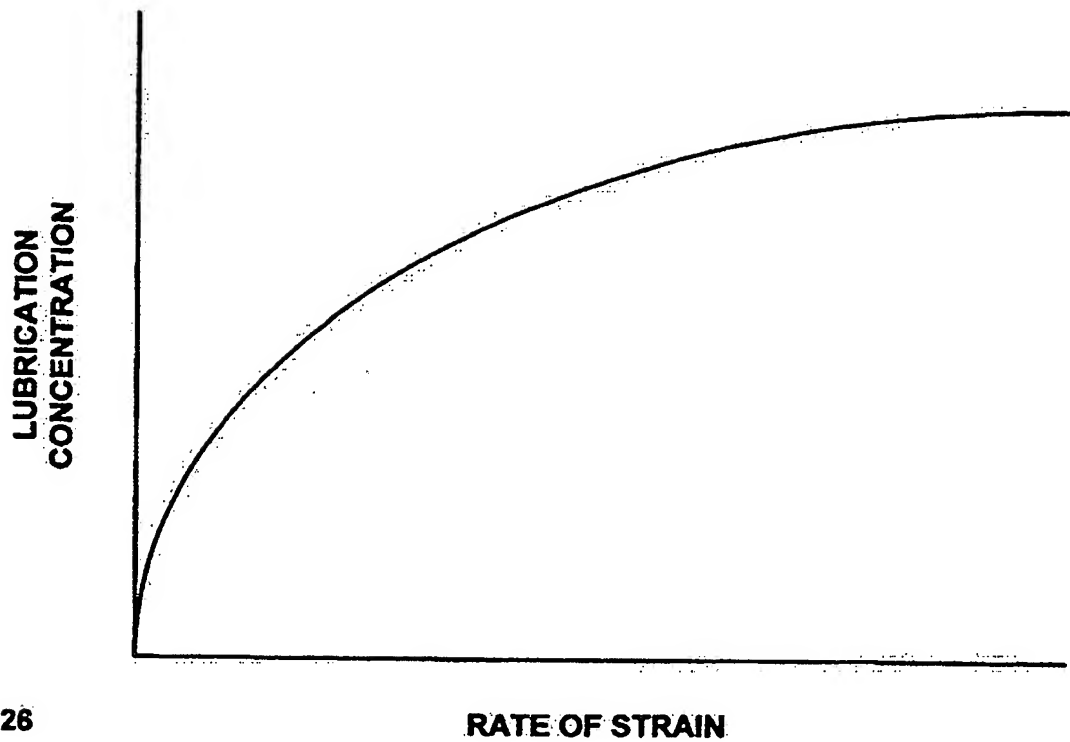


Fig. 26

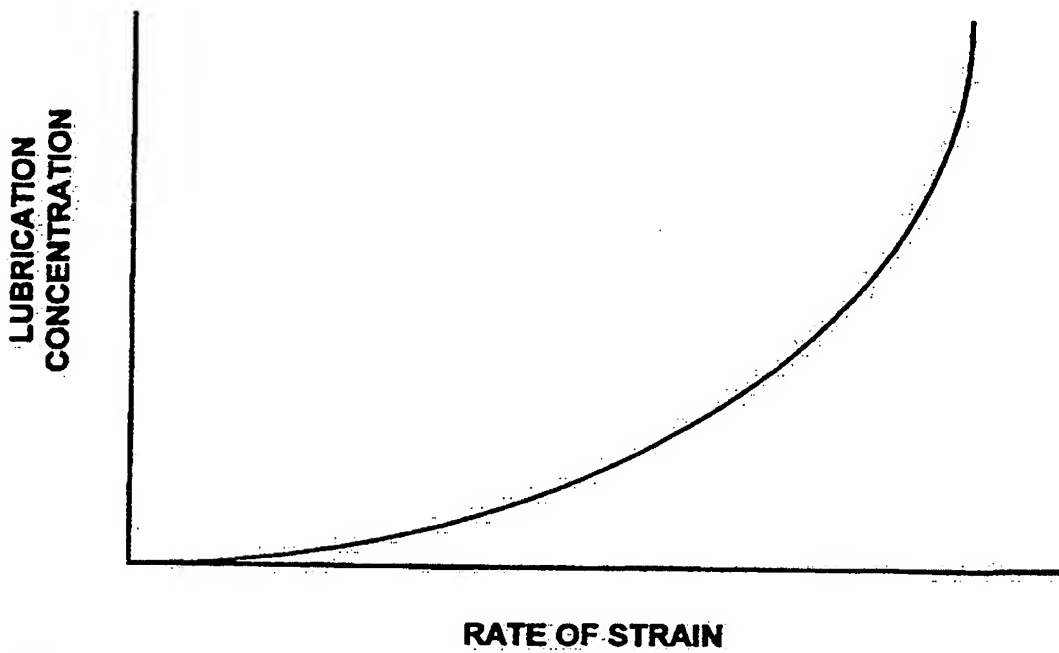


Fig. 27



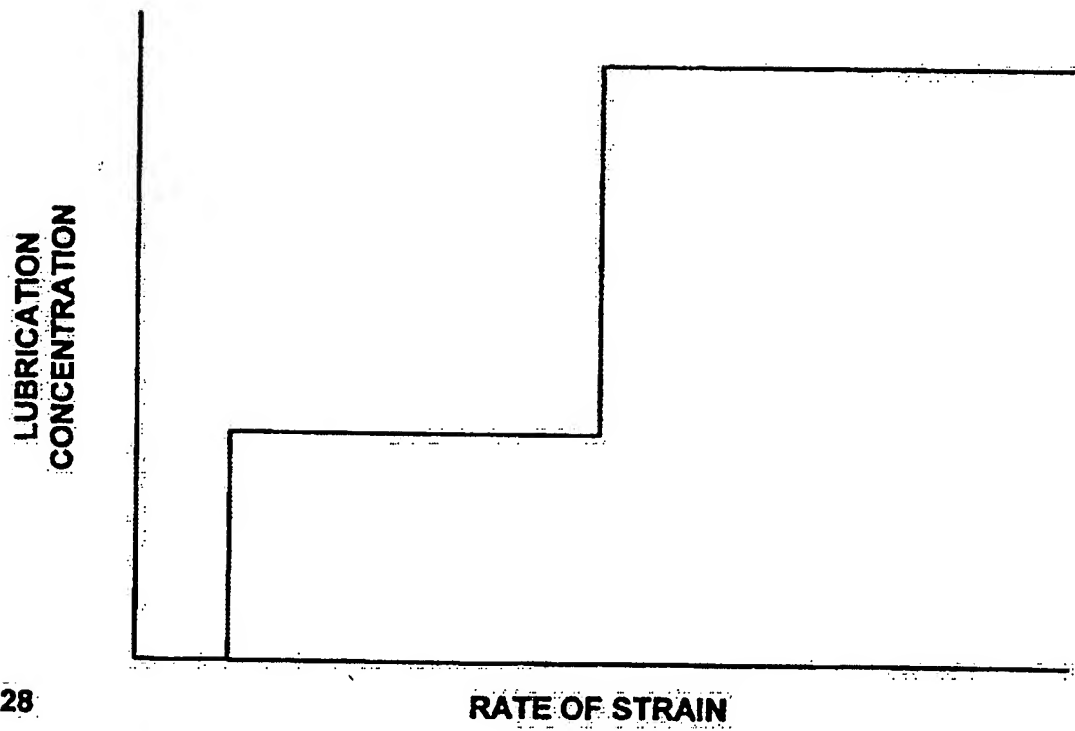


Fig. 28

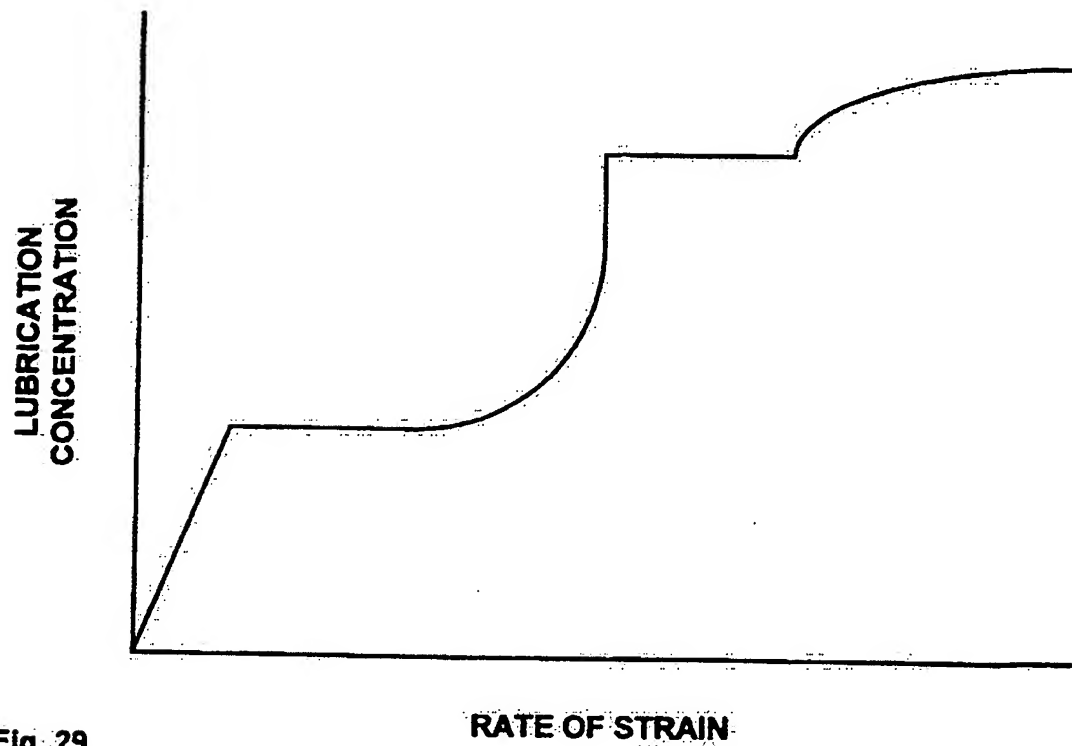
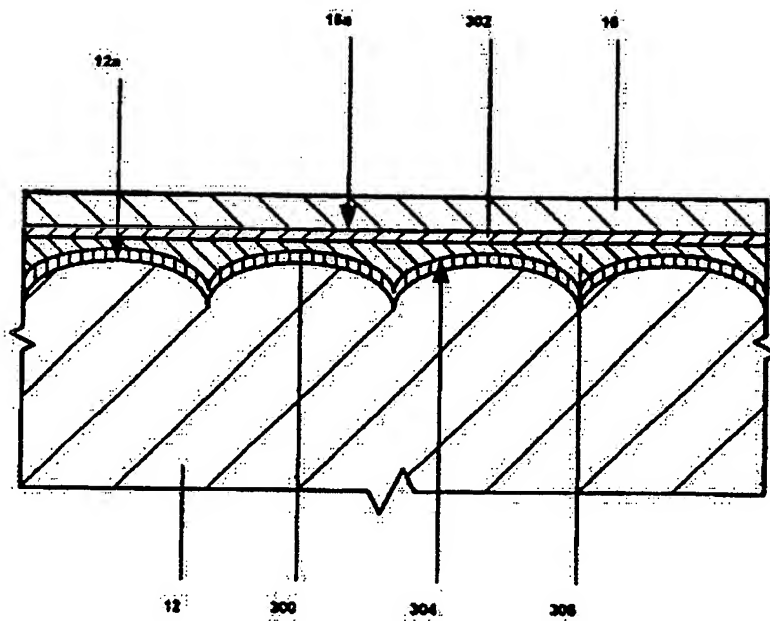


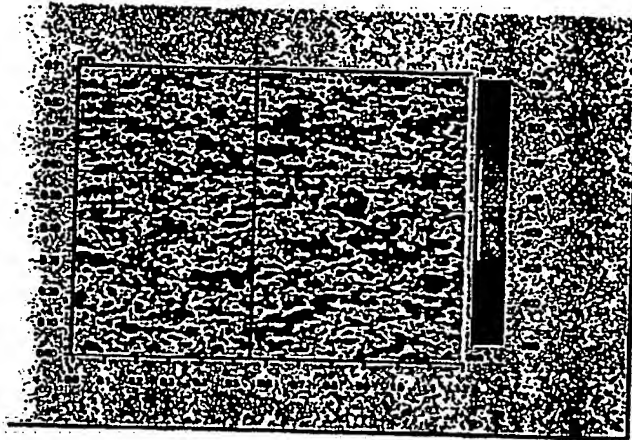
Fig. 29



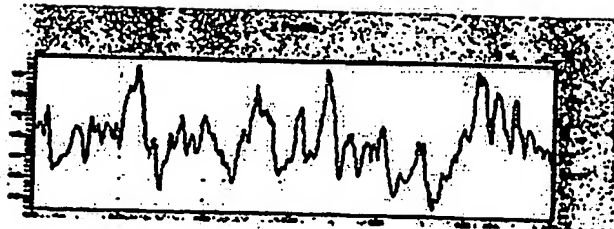
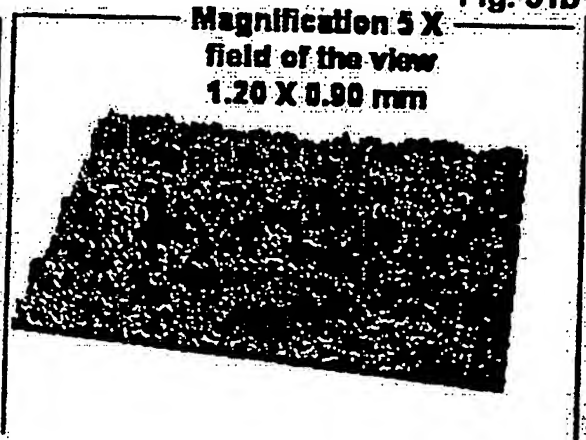
**Fig. 30**

**Typical 3-D Surface View of the D2 Steel  
Cone after Multiple Expansion of the 1-5/8" Pipe**

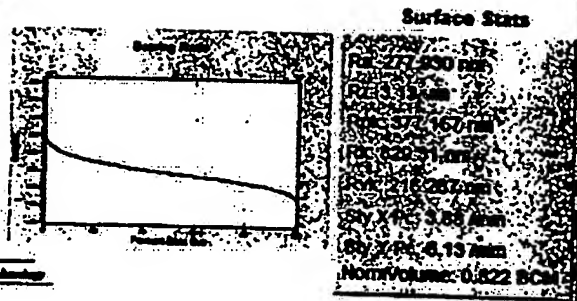
**Fig. 31a**



**Fig. 31b**

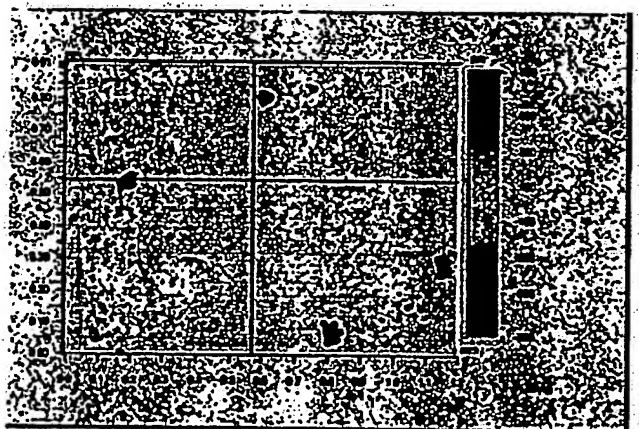


**Fig. 31c**



**Fig. 31d**

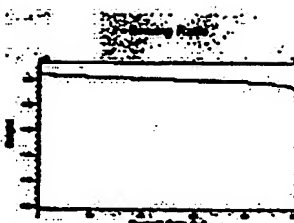
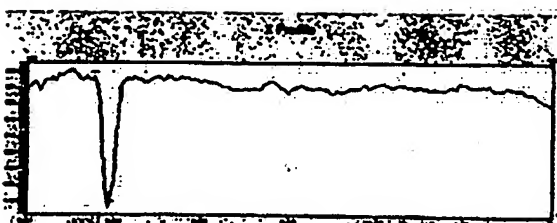
# Typical 3-D Surface View of the Used Advanced DC53 Steel Cone with Phygen Film and REM Polishing



Magnification 5 X  
field of the view  
1.20 X 0.80 mm



Fig. 32b



Surface Stats

Ra: 60.205 nm  
Rz: 1.90 um  
Rpk: 25.009 nm  
Rk: 132.12 nm  
Rmc: 92.963 nm  
Sk: X Pc: 2.217 mm  
Sk: Y Pc: 3.637 mm  
Hv: 0.047 BOM

Fig. 32c

Fig. 32

330

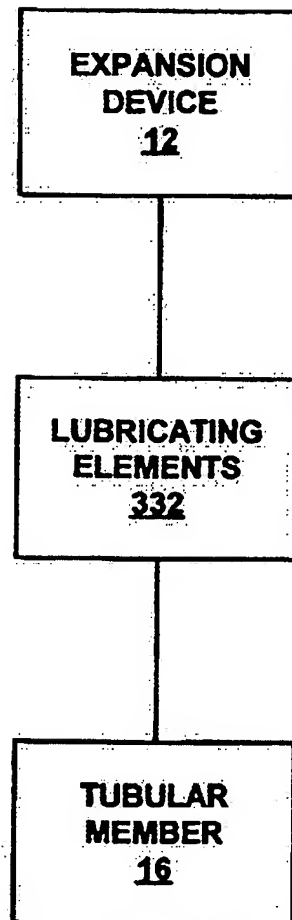


Fig. 33

## **LUBRICATION SYSTEM FOR RADIALLY EXPANDING TUBULAR MEMBERS**

### **Cross-Reference To Related Applications**

**[001]** The present application is the National Stage patent application for PCT patent application serial number PCT/US2004/002122, attorney docket number 25791.225.02, filed on 1/26/2004, which claimed the benefit of the filing date of (1) U.S. provisional patent application serial no. 60/442,938, attorney docket no. 25791.225, filed on January 27, 2003.

**[002]** This invention relates generally to oil and gas exploration, and in particular to forming and repairing wellbore casings to facilitate oil and gas exploration.

### **Background of the Invention**

**[003]** During oil exploration, a wellbore typically traverses a number of zones within a subterranean formation. Wellbore casings are then formed in the wellbore by radially expanding and plastically deforming tubular members that are coupled to one another by threaded connections. Existing methods for radially expanding and plastically deforming tubular members coupled to one another by threaded connections are not always reliable or produce satisfactory results. In particular, the threaded connections can be damaged during the radial expansion process.

**[004]** During expansion, an expansion cone is moved axially through the tubular members. The cone has an outside diameter greater than the inside diameter of the tubular members. Thus, a tremendous amount of friction exists between the cone and the tubular members which results in heat, stress and wear.

**[005]** The expansion cone, or mandrel, is used to permanently mechanically deform the pipe. The cone is moved through the tubing by a differential hydraulic pressure across the cone itself, and/or by a direct mechanical pull or push force. The differential pressure is pumped through an inner-string connected to the cone, and the mechanical force is applied by either raising or lowering the inner string.

**[006]** Progress of the cone through the tubing deforms the steel beyond its elastic limit into the plastic region, while keeping stresses below ultimate yield.

**[007]** Contact between cylindrical mandrel and pipe ID during expansion leads to significant forces due to friction. It would be beneficial to provide a mandrel which could reduce friction during the expansion process.

**[008]** The present invention is directed to overcoming one or more of the limitations of the existing processes for radially expanding and plastically deforming tubular members coupled to one another by threaded connections.

### Summary Of The Invention

[0009] According to a first aspect of the present invention, there is provided an expansion cone for radially expanding multiple tubular members comprising: a body having an annular outer peripheral surface; and at least a portion of the surface being textured with friction reducing reliefs recessed into the surface, wherein the surface comprises a laser dimpled surface.

[0010] Preferably, the multiple tubular members comprise multiple pipeline members.

[0011] Preferably, the friction reducing reliefs are concentrated at a leading edge and a trailing edge of the outer peripheral surface.

[0012] According to a second aspect of the present invention, there is provided a method for radially expanding a tubular member comprising: providing a tubular member having an inside diameter; providing an expansion cone having an annular outer peripheral surface comprising a diameter greater than the inside diameter of the tubular member; texturing the outer peripheral surface with friction reducing reliefs recessed into the surface; and moving the expansion cone axially through the tubular member for radially expanding and plastically deforming the tubular member, wherein the surface comprises a laser dimpled surface.

[0013] Preferably, the tubular member comprises a pipeline member.

[0014] Preferably, the friction reducing reliefs are concentrated at a leading edge and a trailing edge of the outer peripheral surface.

[0015] According to a third aspect of the present invention, there is provided a reduced friction radial expansion apparatus comprising: a plurality of tubular members having an axial passage formed therethrough comprising an inside diameter; an expansion cone having an annular outer peripheral surface comprising an outside diameter greater than the inside diameter of the axial passage; and at least a portion of the outer peripheral surface being textured with friction reducing reliefs recessed into the surface, wherein the surface comprises a laser dimpled surface.

[0016] Preferably, a low friction material is deposited in the reliefs.

[0017] Preferably, a low friction material is deposited in the reliefs. the outer peripheral surface comprises a flush surface comprising a combination of portions of material of the expansion cone and portions of a low friction material deposited in the reliefs.

[0018] Preferably, the plurality of tubular members comprises a plurality of pipeline members.

[0019] Preferably, the friction reducing reliefs are concentrated at a leading edge and a trailing edge of the outer peripheral surface.

### **Brief Description of the Drawings**

**[0021]** Fig. 1a is a fragmentary cross-sectional view illustrating an exemplary embodiment of an apparatus for radially expanding and plastically deforming a tubular member.

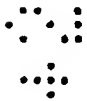
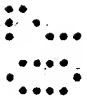
**[0022]** Fig. 1b is a fragmentary cross-sectional illustration of an exemplary embodiment of the operation of the apparatus of Fig. 1a..

**[0023]** Fig. 2 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Figs. 1a and 1b including a lubricant supply.

**[0024]** Fig. 3 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Figs. 1a and 1b including a lubricant supply.

**[0025]** Fig. 4 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Figs. 1a and 1b including a lubricant coating.

**[0026]** Fig. 5 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Figs. 1a and 1b including a lubricant coating.





[0027] Fig. 6 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

[0028] Fig. 7 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 6.

[0029] Fig. 8 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

[0030] Fig. 9 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 8.

[0031] Fig. 10 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

[0032] Fig. 11 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 10.

[0033] Fig. 12 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

[0034] Fig. 13 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 12.

[0035] Fig. 14 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

[0036] Fig. 15 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 14.

[0037] Fig. 16 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

[0038] Fig. 17 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 16.

[0039] Fig. 18 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

**[0040]** Fig. 19 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 18.

**[0041]** Fig. 20 is a fragmentary cross-sectional illustration of an exemplary embodiment of an exemplary portion of the external surface of the expansion device of the apparatus of Figs. 1a and 1b including one or more recesses defined in the external surface.

**[0042]** Fig. 21 is a fragmentary cross-sectional illustration of an exemplary embodiment of the apparatus of Fig. 20.

**[0043]** Fig. 22 is a fragmentary cross-sectional illustration of an exemplary embodiment of leading and trailing edges of the interface between the expansion device of the apparatus of Figs. 1a and 1b and the tubular member during the radial expansion and plastic deformation of the tubular member.

**[0044]** Fig. 23 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

**[0045]** Fig. 24 is a fragmentary cross-sectional illustration of an exemplary embodiment of the interface between the expansion device of the apparatus of Figs. 1a and 1b and the tubular member during the radial expansion and plastic deformation of the tubular member.

**[0046]** Fig. 25 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

**[0047]** Fig. 26 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

**[0048]** Fig. 27 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

**[0049]** Fig. 28 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

**[0050]** Fig. 29 is an exemplary embodiment of a graphical illustration of the concentration distribution of lubrication elements in the external surface of the expansion device of the apparatus of Figs. 1a and 1b.

**[0051]** Fig. 30 is an exemplary embodiment of the apparatus of Figs. 1a and 1b.

[0052] Figs. 31a, 31b, 31c, and 31d are illustrations of an exemplary embodiment of the apparatus of Figs. 1a and 1b.

[0053] Figs. 32a, 32b, 32c, and 32d are illustrations of an exemplary embodiment of the apparatus of Figs. 1a and 1b.

[0054] Fig. 33 is a schematic illustration of a tribological system.

#### **Detailed Description of the Illustrative Embodiments**

[0055] Referring to Figs. 1a and 1b, an exemplary embodiment of an apparatus 10 for radially expanding a tubular member includes an expansion device 12 including one or more expansion surfaces 12a that is coupled to an end of a support member 14.

[0056] In an exemplary embodiment, the expansion device 12 is a conventional commercially available expansion device and/or is provided substantially as described in one or more of the following: (1) U.S. patent application serial no. 09/454,139, attorney docket no. 25791.03.02, filed on 12/3/1999, (2) U.S. patent application serial no. 09/510,913, attorney docket no. 25791.7.02, filed on 2/23/2000, (3) U.S. patent application serial no. 09/502,350, attorney docket no. 25791.8.02, filed on 2/10/2000, (4) U.S. patent application serial no. 09/440,338, attorney docket no. 25791.9.02, filed on 11/15/1999, (5) U.S. patent application serial no. 09/523,460, attorney docket no. 25791.11.02, filed on 3/10/2000, (6) U.S. patent application serial no. 09/512,895, attorney docket no. 25791.12.02, filed on 2/24/2000, (7) U.S. patent application serial no. 09/511,941, attorney docket no. 25791.16.02, filed on 2/24/2000, (8) U.S. patent application serial no. 09/588,946, attorney docket no. 25791.17.02, filed on 6/7/2000, (9) U.S. patent application serial no. 09/559,122, attorney docket no. 25791.23.02, filed on 4/26/2000, (10) PCT patent application serial no. PCT/US00/18635, attorney docket no. 25791.25.02, filed on 7/9/2000, (11) U.S. provisional patent application serial no. 60/162,671, attorney docket no. 25791.27, filed on 11/1/1999, (12) U.S. provisional patent application serial no. 60/154,047, attorney docket no. 25791.29, filed on 9/16/1999, (13) U.S. provisional patent application serial no. 60/159,082, attorney docket no. 25791.34, filed on 10/12/1999, (14) U.S. provisional patent application serial no. 60/159,039, attorney docket no. 25791.36, filed on 10/12/1999, (15) U.S. provisional patent application serial no. 60/159,033, attorney docket no. 25791.37, filed on 10/12/1999, (16) U.S. provisional patent application serial no. 60/212,359, attorney docket no. 25791.38, filed on 6/19/2000, (17) U.S. provisional patent application serial no. 60/165,228, attorney docket no. 25791.39, filed on 11/12/1999, (18) U.S. provisional patent application serial no. 60/221,443, attorney docket no. 25791.45, filed on 7/28/2000, (19) U.S. provisional patent application serial no. 60/221,645, attorney docket no. 25791.46, filed on 7/28/2000, (20) U.S. provisional patent application serial no. 60/233,638, attorney docket no.

25791.47, filed on 9/18/2000, (21) U.S. provisional patent application serial no. 60/237,334, attorney docket no. 25791.48, filed on 10/2/2000, (22) U.S. provisional patent application serial no. 60/270,007, attorney docket no. 25791.50, filed on 2/20/2001, (23) U.S. provisional patent application serial no. 60/262,434, attorney docket no. 25791.51, filed on 1/17/2001, (24) U.S. provisional patent application serial no. 60/259,486, attorney docket no. 25791.52, filed on 1/3/2001, (25) U.S. provisional patent application serial no. 60/303,740, attorney docket no. 25791.61, filed on 7/6/2001, (26) U.S. provisional patent application serial no. 60/313,453, attorney docket no. 25791.59, filed on 8/20/2001, (27) U.S. provisional patent application serial no. 60/317,985, attorney docket no. 25791.67, filed on 9/6/2001, (28) U.S. provisional patent application serial no. 60/3318,386, attorney docket no. 25791.67.02, filed on 9/10/2001, (29) U.S. utility patent application serial no. 09/969,922, attorney docket no. 25791.69, filed on 10/3/2001, (30) U.S. utility patent application serial no. 10/016,467, attorney docket no. 25791.70, filed on December 10, 2001, (31) U.S. provisional patent application serial no. 60/343,674, attorney docket no. 25791.68, filed on 12/27/2001; and (32) U.S. provisional patent application serial no. 60/346,309, attorney docket no. 25791.92, filed on 01/07/02, the disclosures of which are incorporated herein by reference. In several alternative embodiments, the expansion device 12 is, or includes, a conventional commercially available rotary expansion device such, for example, those available from Weatherford International.

**[0057]** In an exemplary embodiment, the apparatus 10 is operated to radially expand and plastically deform a tubular member 16 by displacing and/or rotating the expansion device 12 relative to the tubular member 16 within a preexisting structure such as, for example, a wellbore 18 that traverses a subterranean formation 20. In an exemplary embodiment, during the operation of the apparatus 10, the expansion surface 12a of the expansion device 12 engages at least a portion of the interior surface 16a of the tubular member 16.

**[0058]** In an exemplary embodiment, the apparatus 10 is operated substantially as described in one or more of the following: (1) U.S. patent application serial no. 09/454,139, attorney docket no. 25791.03.02, filed on 12/3/1999, (2) U.S. patent application serial no. 09/510,913, attorney docket no. 25791.7.02, filed on 2/23/2000, (3) U.S. patent application serial no. 09/502,350, attorney docket no. 25791.8.02, filed on 2/10/2000, (4) U.S. patent application serial no. 09/440,338, attorney docket no. 25791.9.02, filed on 11/15/1999, (5) U.S. patent application serial no. 09/523,460, attorney docket no. 25791.11.02, filed on 3/10/2000, (6) U.S. patent application serial no. 09/512,895, attorney docket no. 25791.12.02, filed on 2/24/2000, (7) U.S. patent application serial no. 09/511,941, attorney docket no. 25791.16.02, filed on 2/24/2000, (8) U.S. patent application serial no. 09/588,946, attorney docket no. 25791.17.02, filed on

6/7/2000, (9) U.S. patent application serial no. 09/559,122, attorney docket no. 25791.23.02, filed on 4/26/2000, (10) PCT patent application serial no. PCT/US00/18635, attorney docket no. 25791.25.02, filed on 7/9/2000, (11) U.S. provisional patent application serial no. 60/162,671, attorney docket no. 25791.27, filed on 11/1/1999, (12) U.S. provisional patent application serial no. 60/154,047, attorney docket no. 25791.29, filed on 9/16/1999, (13) U.S. provisional patent application serial no. 60/159,082, attorney docket no. 25791.34, filed on 10/12/1999, (14) U.S. provisional patent application serial no. 60/159,039, attorney docket no. 25791.36, filed on 10/12/1999, (15) U.S. provisional patent application serial no. 60/159,033, attorney docket no. 25791.37, filed on 10/12/1999, (16) U.S. provisional patent application serial no. 60/212,359, attorney docket no. 25791.38, filed on 6/19/2000, (17) U.S. provisional patent application serial no. 60/165,228, attorney docket no. 25791.39, filed on 11/12/1999, (18) U.S. provisional patent application serial no. 60/221,443, attorney docket no. 25791.45, filed on 7/28/2000, (19) U.S. provisional patent application serial no. 60/221,645, attorney docket no. 25791.46, filed on 7/28/2000, (20) U.S. provisional patent application serial no. 60/233,638, attorney docket no. 25791.47, filed on 9/18/2000, (21) U.S. provisional patent application serial no. 60/237,334, attorney docket no. 25791.48, filed on 10/2/2000, (22) U.S. provisional patent application serial no. 60/270,007, attorney docket no. 25791.50, filed on 2/20/2001, (23) U.S. provisional patent application serial no. 60/262,434, attorney docket no. 25791.51, filed on 1/17/2001, (24) U.S. provisional patent application serial no. 60/259,486, attorney docket no. 25791.52, filed on 1/3/2001, (25) U.S. provisional patent application serial no. 60/303,740, attorney docket no. 25791.61, filed on 7/6/2001, (26) U.S. provisional patent application serial no. 60/313,453, attorney docket no. 25791.59, filed on 8/20/2001, (27) U.S. provisional patent application serial no. 60/317,985, attorney docket no. 25791.67, filed on 9/6/2001, (28) U.S. provisional patent application serial no. 60/3318,386, attorney docket no. 25791.67.02, filed on 9/10/2001, (29) U.S. utility patent application serial no. 09/969,922, attorney docket no. 25791.69, filed on 10/3/2001, (30) U.S. utility patent application serial no. 10/016,467, attorney docket no. 25791.70, filed on December 10, 2001, (31) U.S. provisional patent application serial no. 60/343,674, attorney docket no. 25791.68, filed on 12/27/2001; and (32) U.S. provisional patent application serial no. 60/346,309, attorney docket no. 25791.92, filed on 01/07/02, the disclosures of which are incorporated herein by reference. In several alternative embodiments, the expansion device 12 is operated like, or includes operational features of, a conventional commercially available rotary expansion device such, for example, those available from Weatherford International.

**[0059]** In an exemplary embodiment, as illustrated in Fig. 2, the apparatus 10 further includes a lubricant supply 20, and during the operation of the apparatus 10, the lubricant supply injects a lubricating material 22 into an annulus 24 defined between one or more the expansion surfaces 12a of the expansion device 12 and the internal surface 16a of the tubular member 16. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the lubricating material 22 includes fluidic and/or solid lubricating materials.

**[0060]** In an exemplary embodiment, as illustrated in Fig. 3, the expansion device 12 of the apparatus 10 further includes an internal lubricant supply 30, and during the operation of the apparatus 10, the lubricant supply injects a lubricating material 32 into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the lubricating material 32 includes fluidic and/or solid lubricating materials. In an exemplary embodiment, the lubricant supply injects the lubricating material 32 into one or more recesses defined in the expansion surface 12a of the expansion device 12.

**[0061]** In an exemplary embodiment, as illustrated in Fig. 4, a layer of a lubricating film 40 is coupled to at least a portion of one or more of the expansion surfaces 12a of the expansion device 12 of the apparatus 10 such that, during the operation of the apparatus, at least a portion of the lubricating film 40 is released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the lubricating film 40 includes fluidic and/or solid lubricating materials. In an exemplary embodiment, the thickness and/or composition of the film 40 are non-uniform.

**[0062]** In an exemplary embodiment, as illustrated in Fig. 5, layers 50a and 50b of a lubricating film are coupled to portions of one or more of the expansion surfaces 12a of the expansion device 12 of the apparatus 10 such that, during the operation of the apparatus, at least a portion of the layers of lubricating film, 50a and 50b, are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the layers, 50a and 50b, of lubricating film are deposited within recesses, 52a and 52b, respectively, defined within the expansion surface 12a. In an exemplary embodiment, the lubricating film, 50a and 50b, include fluidic and/or solid lubricating materials. In an exemplary embodiment, the thickness and/or composition of the films, 50a and/or 50b, are non-uniform.

**[0063]** In an exemplary embodiment, as illustrated in Figs. 6 and 7, one or more portions of the expansion surfaces 12a of the apparatus 10 define recesses 60a, 60b, 60c, and 60d, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses, 60a, 60b, 60c, and 60d, are substantially identical and equally spaced cylindrical cavities defined within the expansion surface 12a of the expansion device. In several alternative embodiments, one or more of the recesses 60 may be different in geometry from one or more of the other recesses 60. In several alternative embodiments, the spacing between the recesses 60 may be unequal.

**[0064]** In an exemplary embodiment, as illustrated in Figs. 8 and 9, one or more portions of the expansion surfaces 12a of the apparatus 10 define recesses 80a, 80b, 80c, and 80d, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses, 80a, 80b, 80c, and 80d, are cylindrical cavities of varying depths defined within the expansion surface 12a of the expansion device. In an exemplary embodiment, the placement of the recesses 80 is such that the pair of recesses, 80a and 80b, are offset from the other pair of recesses, 80c and 80d. In several alternative embodiments, one or more of the recesses 80 may be different in geometry from one or more of the other recesses 80. In several alternative embodiments, the spacing between the recesses 80 may be unequal.

**[0065]** In an exemplary embodiment, as illustrated in Figs. 10 and 11, one or more portions of the expansion surfaces 12a of the apparatus 10 define criss-crossing recesses 100a, 100b, 100c, and 100d, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses, 100a and 100b, are substantially parallel to one another,



and the recesses, 100c and 100d, are substantially parallel to one another, and the recesses, 100a and 100b, are both substantially orthogonal to the recesses, 100c and 100d. In several alternative embodiments, one or more of the recesses 100 may be different in geometry and orientation from one or more of the other recesses 100. In several alternative embodiments, the spacing between the recesses 100 may be unequal.

**[0066]** In an exemplary embodiment, as illustrated in Fig. 12, one or more portions of the expansion surfaces 12a of the apparatus 10 define recesses 120a, 120b, 120c, 120d, 120e and 120f, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses 120 are substantially identical cylindrical recesses that are defined within, and randomly distributed on, the expansion surface 12a of the expansion device 12. In several alternative embodiments, one or more of the recesses 120 may be different in geometry and orientation from one or more of the other recesses 120.

**[0067]** In an exemplary embodiment, as illustrated in Fig. 13, one or more portions of the expansion surfaces 12a of the apparatus 10 define recesses 130a, 130b, 130c, 130d, 130e and 130f, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses 130 are cylindrical recesses that are defined within, and randomly distributed on, the expansion surface 12a of the expansion device 12. In an exemplary embodiment, the volumetric geometry of the recesses 130 are randomly selected.

**[0068]** In an exemplary embodiment, as illustrated in Figs. 14 and 15, one or more portions of the expansion surfaces 12a of the apparatus 10 define one or more recesses 140, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the boundaries of the recess 140 include one or more linear and/or non-linear boundaries and



the depth of the recess is random in all directions. In several alternative embodiments, one or more of the recesses 140 may be different in geometry and orientation from one or more of the other recesses 140. In several alternative embodiments, the spacing between the recesses 140 may be unequal and/or random. In several alternative embodiments, the depth of the recess 140 may be constant.

**[0069]** In an exemplary embodiment, as illustrated in Figs. 16 and 17, one or more portions of the expansion surfaces 12a of the apparatus 10 define recesses 160a, 160b, 160c, and 160d, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recesses, 160a, 160b, 160c, and 160d, are substantially identical and equally spaced cylindrical cavities having completely curved walls defined within the expansion surface 12a of the expansion device. In several alternative embodiments, one or more of the recesses 160 are substantially identical in geometry to the dimples found in one or more conventional golf balls. In several alternative embodiments, one or more of the recesses 160 may be different in geometry from one or more of the other recesses 160. In several alternative embodiments, the spacing between the recesses 160 may be unequal.

**[0070]** In an exemplary embodiment, as illustrated in Figs. 18 and 19, one or more portions of the expansion surfaces 12a of the apparatus 10 define a recess 180, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recess 180 is an etched surface having a non-uniform pattern of pits 180a. In several alternative embodiments, the depth of the pits 180a is non-uniform.

**[0071]** In an exemplary embodiment, as illustrated in Figs. 20 and 21, one or more portions of the expansion surfaces 12a of the apparatus 10 define a recess 190, that may, for example, contain the lubricant material 22, the lubricant material 32, the lubricant film 40, and/or the lubricant film 50, such that, during the operation of the apparatus, at least a portion of the lubricant materials and/or the lubricant films are released into the annulus 24. In this manner, the amount of energy and/or power required to radially expand and plastically deform the

tubular member 16 using the expansion device 12 is reduced. In an exemplary embodiment, the recess 190 is a knurled surface having a uniform pattern of pits 190a. In several alternative embodiments, the pattern of the pits 190a and/or the depth of the pits 190a is non-uniform.

[0072] In an exemplary embodiment, as illustrated in Fig. 22, during the operation of the apparatus 10, the interface between the expansion surface 12a of the expansion device 12 and the interior surface 16a of the tubular member 16 includes a leading edge portion 220 and a trailing edge portion 222. In an exemplary embodiment, as illustrated in Fig. 23, the concentration of lubrication is increased in the leading and trailing edge portions, 220 and 222, respectively, in order to reduce the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12.

[0073] In several exemplary embodiments, the concentration of lubrication within a specific portions of the expansion surface 12a of the expansion device 12 is increased by increasing one or more of the following: 1) the flow of the lubricant materials 22 and/or 32 into the annulus 24 surrounding the specific portion; 2) the volume of the films 40 and/or 50 applied to the specific portion; 3) the density of the recesses 60, 80, 100, 120, 130, 140, 160, 180, and/or 200 within the specific portion; and/or 4) the normalized oil volume within the specific portion.

[0074] In an exemplary embodiment, as illustrated in Fig. 24, during the operation of the apparatus 10, recesses, 240a and 240b, defined within the expansion surface 12a of the expansion device 12, provide a support for, and define lubrication ball bearings, 242a and 242b, for lubricating the interface between the expansion surface of the expansion device and the internal surface 16a of the tubular member. In this manner, the lubricating materials derived from one or more of the following: the lubricant materials 22 and/or 32 and/or the films 40 and/or 50 are formed into a ball-like fluidic lubricating structure that act like lubricating ball bearings thereby reducing the amount of energy and/or power required to radially expand and plastically deform the tubular member 16 using the expansion device 12.

[0075] In an exemplary embodiment, during the operation of the apparatus 10, the rate of strain of the tubular member 16 varies as a function of the geometry of the expansion surface 12a of the expansion device. Thus, for example, certain portions of the tubular member 16 that interface with the expansion surface 12a of the expansion device 12 may experience rates of strain that are different from other portions of the tubular member that interface with the expansion surface of the expansion device. In an exemplary embodiment, during the operation of the apparatus 10, the concentration of lubrication is increased in those areas having greater rates of strain as compared with those areas having lesser rates of strain in order to reduce the amount of energy and/or power required to radially expand and plastically deform the tubular

member 16 using the expansion device 12. In an exemplary embodiment, as illustrated in Fig. 25, the relationship between the concentration of lubrication and the rate of strain is a linear relationship. In an alternative embodiment, as illustrated in Fig. 26, the relationship between the concentration of lubrication and the rate of strain is a non-linear relationship having a decreasing slope with increasing rate of strain. In an alternative embodiment, as illustrated in Fig. 27, the relationship between the concentration of lubrication and the rate of strain is a non-linear relationship having an decreasing slope with increasing rate of strain. In an alternative embodiment, as illustrated in Fig. 28, the relationship between the concentration of lubrication and the rate of strain includes one or more step functions. In an alternative embodiment, as illustrated in Fig. 29, the relationship between the concentration of lubrication and the rate of strain includes one or more of the characteristics of Figs. 25-28.

**[0076]** In several exemplary embodiments, the concentration of lubrication within a specific portions of the expansion surface 12a of the expansion device 12 is increased by increasing one or more of the following: 1) the flow of the lubricant materials 22 and/or 32 into the annulus 24 surrounding the specific portion; 2) the volume of the films 40 and/or 50 applied to the specific portion; 3) the density of the recesses 60, 80, 100, 120, 130, 140, 160, 180, and/or 200 within the specific portion; and/or 4) the normalized oil volume within the specific portion.

**[0077]** More generally, in several exemplary embodiments, the concentration of lubrication within a specific portions of the expansion surface 12a of the expansion device 12 is controlled by adjusting one or more of the following: 1) the flow of the lubricant materials 22 and/or 32 into the annulus 24 surrounding the specific portion; 2) the volume of the films 40 and/or 50 applied to the specific portion; 3) the density of the recesses 60, 80, 100, 120, 130, 140, 160, 180, and/or 200 within the specific portion; and/or 4) the normalized oil volume within the specific portion.

**[0078]** In several exemplary embodiments, during at least a portion of the operation of the apparatus 10, at least portions of the annulus 24 between the expansion surface 12a of the expansion device 12 and the internal surface 16a of the tubular member 16 may be reduced in thickness to zero thereby permitting the at least a portion of the expansion surface of the expansion device to contact at least a portion of the interior surface of the tubular member.

**[0079]** In several exemplary embodiments, the lubricating films 40 and/or 50 include a physical vapor deposition Chromium Nitride coating commercially available from Phygen, Inc, in Minneapolis, Minnesota. In several exemplary embodiments, the lubricating films 40 and/or 50 are coupled to an expansion surface 12a fabricated from DC53 steel, new cold die steel,

commercially available from Daido Steel Co. in Japan and/or International Steel Co., in Florence, Kentucky.

**[0080]** In several exemplary embodiments, the surface texture of at least a portion of one or more of the expansion surfaces 12a and/or one or more of the recesses 60, 80, 100, 120, 140, 160, 180, 200 and/or 240 is provided by polishing a surface roughness into the expansion surfaces and/or recesses using commercially available methods and apparatus available from REM Chemicals, in Brenham, Texas.

**[0081]** In several exemplary embodiments, the lubricant materials 22 and/or 32 include various environmentally friendly lubricant materials commercially available from Oleon, Inc. in Belgium and/or as lubricant materials # 2633-179 - 1, 2, 3, 4, 5, and 6 from Houghton International, Valley Forge, Pennsylvania. In several exemplary embodiments, the lubricant materials 22 and/or 32 include Radiagreen eme salt.

**[0082]** Referring to Fig. 30, in an exemplary embodiment, at least a portion of one or more of the expansion surfaces 12a of the expansion device 12 is textured and a lubricating film 300 is coupled to at least a portion of the textured expansion surface. Furthermore, in an exemplary embodiment, at least a portion of the interior surface 16a of the tubular member 16 includes a lubricating film 302, and an annulus 304 defined between the expansion device 12 and the tubular member 16 includes a lubricant material 306. In an exemplary embodiment, the lubricating film 300 is harder and more resistant to abrasion than the lubricating film 302. In an exemplary embodiment, the use of a textured expansion surface 12a, the lubricating film 300, the lubricating film 302, and the lubricant film 306 during the operation of the apparatus 10 provided a friction coefficient less than about 0.02. In an exemplary embodiment, the textured expansion surface 12a is provided using one or more of the recesses 60, 80, 100, 120, 140, 160, 180, 200 and/or 240 described above and/or by texturing the expansion surface 12a. In an exemplary embodiment, the expansion surface 12a is fabricated from a DC53 tool steel, commercially available from Daido Steel in Japan, the texturing of the expansion surface 12a is provided by polishing the expansion surface using the commercially available products and services of REM Chemicals in Brenham, Texas, the lubricating film 300 includes a hard film Phygen 2, physical vapor deposition Chromium Nitride coating, commercially available from Phygen, Inc., in Minneapolis, MN, the lubricating film 302 includes a Polytetrafluoroethylene (PTFE) based soft film coating, commercially available as a Brighton 9075 coating from Brighton Laboratories, in Howell, Michigan, and the lubricant material 306 includes a commercially available lubricant from Houghton International, in Valley Forge, Pennsylvania.

[0083] In an exemplary embodiment, the surface texture of the expansion surface 12a and/or one or more of the recesses 60, 80, 100, 120, 140, 160, 180, 200 and/or 240 is characterized by one or more of the following parameters:  $R_a$ ,  $R_q$ ,  $R_{sk}$ ,  $R_{ku}$ ,  $R_p$ ,  $R_v$ ,  $R_t$ ,  $R_{pm}$ ,  $R_{vm}$ ,  $R_z$ ,  $R_{pk}$ ,  $R_k$ ,  $R_{vk}$ ,  $M_{r1}$ ,  $M_{r2}$ ,  $R_{pk}/R_k$ ,  $R_{vk}/R_k$ ,  $R_{pk}/R_{vk}$ , X Slope  $R_q$ , Y Slope  $R_q$ , NVOL, and/or SAI. In an exemplary embodiment, the measurement of these parameters is provided using the commercially available services of Michigan Metrology LLC in Livonia, Michigan.

[0084]  $R_a$  refers to the arithmetic average of the absolute values of the surface height deviations measured from the best fitting plane, cylinder or sphere.  $R_a$  is described by:

$$R_a = \frac{1}{A} \iint_a |Z(x,y)| dx dy$$

where  $Z(x,y)$  = the vertical position of a position on the surface at coordinates  $x$  and  $y$ .

[0085]  $R_q$  refers to the RMS (Standard Deviation) or "first moment" of the height distribution, as described by:

$$R_q = \sqrt{\frac{1}{A} \iint_a (Z(x,y))^2 dx dy}$$

[0086]  $R_{sk}$  refers to the skew or "second moment" of the height distribution, as described by:

$$R_{sk} = \frac{1}{R_q^3} \iint_a (Z(x,y))^3 dx dy$$

[0087]  $R_{ku}$  refers to the "kurtosis" or the "third moment" of the height distribution, described by:

$$R_{ku} = \frac{1}{R_q^4} \iint_a (Z(x,y))^4 dx dy$$

[0088]  $R_p$ ,  $R_v$ , and  $R_t$  are parameters evaluated from the absolute highest and lowest points found on the surface.  $R_p$  is the height of the highest point,  $R_v$  is the depth of the lowest point and  $R_t$  is found from  $R_p - R_v$ . The  $R_{pm}$ ,  $R_{vm}$ , and  $R_z$  parameters are evaluated from an average of the heights and depths of the extreme peaks and valleys.  $R_{pm}$  is found by averaging the heights of the ten (10) highest peaks found over the complete 3D image.  $R_{vm}$  is found by averaging the depths of the ten (10) lowest valleys found over the complete 3D image.  $R_z$  is then found by  $(R_{pm} - R_{vm})$ .

[0089] The parameters  $R_{pk}$ ,  $R_k$ ,  $R_{vk}$ ,  $M_{r1}$ , and  $M_{r2}$  are all derived from the bearing ratio curve based on the DIN 4776 standard, the disclosure of which is incorporated herein by reference. The bearing area curve is a measure of the relative cross-sectional area a plane passing through the measured surface, from the highest peak to the lowest valley, would encounter.  $R_{pk}$  is a measure of the peak height above the nominal/core roughness.  $R_k$  is a measure of the nominal or "core" roughness ("peak to valley") of the surface.  $R_{vk}$  is a measure of the valley depth below the nominal/core roughness.  $M_{r1}$ , the peak material ratio, indicates the percentage

of material that comprise the peak structures associate with  $R_{pk}$ .  $M_{r2}$  is a measure of the valley material ratio, with  $(100\%-M_{r2})$  representing the percentage of material that comprise the valley structures associated with  $R_{vk}$ .

**[0090]**  $R_{pk}/R_k$ ,  $R_{vk}/R_k$ ,  $R_{pk}/R_{vk}$ : the ratios of the various bearing ratio parameters may be helpful in further understanding the nature of a particular surface texture. In some instances two surfaces with indistinguishable average roughness ( $R_a$ ) may be easily distinguished by the ratio such as  $R_{pk}/R_k$ . For example, a surface with high peaks as opposed to a surface with deep valleys may have the same  $R_a$  but with vastly different  $R_{pk}/R_k$  values.

**[0091]** X Slope  $R_q$ , Y Slope  $R_q$ : The parameters X Slope  $R_q$  and Y Slope  $R_q$  are found by calculating the Standard Deviation (i.e. RMS or  $R_q$ ) of the slopes of the surface along the X and Y directions respectively. The slope is found by taking the derivative of the surface profiles along each direction, using the lateral resolution of the measurement area as the point spacing. Analytically, X Slope  $R_q$  and Y Slope  $R_q$  are given by:

$$X \text{ Slope } R_q = \left( \iint_a \left( \frac{\partial Z(x,y)}{\partial x} - \left\langle \frac{\partial Z(x,y)}{\partial x} \right\rangle \right)^2 dx dy \right)^{1/2} \quad Y \text{ Slope } R_q = \left( \iint_a \left( \frac{\partial Z(x,y)}{\partial y} - \left\langle \frac{\partial Z(x,y)}{\partial y} \right\rangle \right)^2 dx dy \right)^{1/2}$$

Where the brackets,  $\langle \rangle$ , represent the average value of all slopes in the relevant direction

**[0092]** NVOL: The Normalized Volume (NVOL) of the surface is found by calculating the volume contained by the surface and a "plane" that is placed near the top of the surface. The placement of the reference plane is typically done on a statistical basis to assure that the very high peak locations are not used as the reference point for the plane. Once the volume is calculated (e.g. in units of  $\text{cm}^3$ ), the result is "normalized" to the cross sectional area of the plane (i.e. units of  $\text{m}^2$ ). Other units of NVOL are BCM, which is an acronym for "Billions of Cubic Microns per Inch Squared".

**[0093]** The Surface Area Index (SAI) evaluates the surface area at the lateral resolution of the measured surface as compared to that of a perfectly flat/smooth surface. The calculation involves fitting triangular patches between the measured points and adding up the total area of all patches. A ratio is then formed of the total surface area measured and the nominal flat area of measurement. This analysis is a precursor to a complete fractal analysis of the surface. Since SAI is a ratio, it is a unit-less quantity.

**[0094]** In an exemplary embodiment, one or more of the parameters  $R_a$ ,  $R_q$ ,  $R_{sk}$ ,  $R_{ku}$ ,  $R_p$ ,  $R_v$ ,  $R_t$ ,  $R_{pm}$ ,  $R_{vm}$ ,  $R_z$ ,  $R_{pk}$ ,  $R_k$ ,  $R_{vk}$ ,  $M_{r1}$ ,  $M_{r2}$ ,  $R_{pk}/R_k$ ,  $R_{vk}/R_k$ ,  $R_{pk}/R_{vk}$ , X Slope  $R_q$ , Y Slope  $R_q$ , NVOL, and/or SAI described above are defined as described at the following website:

<http://www.michmet.com>, the disclosure of which is incorporated herein by reference.

[0095] In an exemplary implementation, an apparatus 10 having an expansion device 12 including an expansion surface 12a fabricated from conventional D2 steel was operated to expand a plurality of tubular members 16 fabricated from low carbon steel using a water base mud media as a lubricating material. Fig. 31a is top view of a portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 31b is a magnified perspective view of the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 31c is a graphical illustration of the surface profile of a sliced portion of the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 31d is a graphical and tabular illustration of the bearing ratio,  $R_a$ ,  $R_z$ ,  $R_{pk}$ ,  $R_k$ ,  $R_{vk}$ ,  $Sty\ X\ Pc$  (X Slope  $R_q$ ),  $Sty\ Y\ Pc$  (Y Slope  $R_q$ ), and NVOL for the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. As illustrated in Fig. 31d, the exemplary implementation had the following characteristics:

Parameter	Value
$R_a$	277.930 nm
$R_z$	3.13 nm
$R_{pk}$	377.167 nm
$R_k$	829.31 nm
$R_{vk}$	216.287 nm
Slope $R_q$	3.88/mm
Y Slope $R_q$	6.13/mm
NVOL	0.822 BCM

In the exemplary implementation of the embodiment of Figs. 31a, 31b, 31c, and 31d, the forces required to overcome friction during the operation of the apparatus 10 were about 45% of all the expansion forces required to radially expand and plastically deform the tubular member 16 and the coefficient of friction for the interface between the expansion surfaces 12a of the expansion device 12 and the interior surface 16a of the tubular member was about 0.125.

[0096] In an exemplary implementation, an apparatus 10 having an expansion device 12 including an expansion surface 12a fabricated from DC53 tool steel, available from Daido Steel in Japan, was operated to expand a plurality of tubular members 16 fabricated from low carbon



steel. The expansion surface 12a was surface polished using the services of REM Chemicals in Brenham, Texas and a lubricating film including a Chromium Nitride coating, available from Phygen, Inc., in Minneapolis, Minnesota, was coupled to the expansion surface. Fig. 32a is top view of a portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 32b is a magnified perspective view of the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 32c is a graphical illustration of the surface profile of a sliced portion of the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. Fig. 32d is a graphical and tabular illustration of the bearing ratio,  $R_a$ ,  $R_z$ ,  $R_{pk}$ ,  $R_k$ ,  $R_{vk}$ ,  $Sty\ X\ Pc\ (X\ Slope\ R_q)$ ,  $Sty\ Y\ Pc\ (Y\ Slope\ R_q)$ , and NVOL for the portion of the expansion surface 12a of the expansion device 12 of the apparatus after repeated radial expansions and plastic deformations of the tubular members 16 using the apparatus 10. As illustrated in Fig. 32d, the exemplary implementation had the following characteristics:

Parameter	Value
$R_a$	60.205 nm
$R_z$	1.99 nm
$R_{pk}$	25.009 nm
$R_k$	152.12 nm
$R_{vk}$	92.963 nm
Slope $R_q$	2.21/mm
Y Slope $R_q$	3.53/mm
NVOL	0.047 BCM

In the exemplary implementation of the embodiment of Figs. 32a, 32b, 32c, and 32d, the forces required to overcome friction during the operation of the apparatus 10 were between about 30% to 8% of all the expansion forces required to radially expand and plastically deform the tubular member 16 and the coefficient of friction for the interface between the expansion surfaces 12a of the expansion device 12 and the interior surface 16a of the tubular member was about 0.06. Furthermore, in the exemplary embodiment of Figs. 32a, 32b, 32c, and 32d, the bearing ratio of the expansion surface 12a of the expansion device 12 was greater than 75% on 60% of the  $R_z$  surface roughness.

[0097] A comparison of the exemplary implementation illustrated in Figs. 31a, 31b, 31c, and



31d and the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d indicated that an example of a preferred surface texture for an expansion surface 12a of the expansion device 12 during the radial expansion and plastic deformation of the tubular member 16 was a surface texture having a plateau-like surface with relatively deep recesses as provided in the exemplary implementation of Figs. 32a, 32b, 32c, and 32d. This was an unexpected result.

[0098] Furthermore, a comparison of the exemplary implementation illustrated in Figs. 31a, 31b, 31c, and 31d and the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d also indicated that the expansion surface of the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d provided not only a smoother surface, as measured by  $R_a$  and/or  $R_z$ , but also provided much higher load capacity, as measured by the bearing ratio. Furthermore, the bearing ratio for the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d had much less variation in value than the bearing ratio for the exemplary implementation illustrated in Figs. 31a, 31b, 31c, and 31d. Thus, in a preferred embodiment, the bearing ratio varies less than about 15% across the expansion surface 12a. In addition, the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d provided a bearing ratio about double that of the exemplary implementation illustrated in Figs. 31a, 31b, 31c, and 31d. For example, at the level of 60%  $R_z$ , the percentage of the material supporting a load on the exemplary implementation illustrated in Figs. 32a, 32b, 32c, and 32d was about 80% in comparison to about 37% for the exemplary implementation illustrated in Figs. 31a, 31b, 31c, and 31d.

[0099] In an exemplary embodiment, the preferred surface texture of the exemplary implementation of Figs. 32a, 32b, 32c, and 32d, a plateau-like surface with relatively deep recesses, is provided by laser dimpling the expansion surface 12a.

[00100] In an exemplary embodiment, as illustrated in Fig. 33, the apparatus 10 provides a tribological system 330 including the expansion device 12, the tubular member 16, and one or more lubricating elements 332 such as, for example, those elements described above for reducing friction between the expansion surfaces 12a of the expansion device and the tubular member during the operation of the apparatus 10. In an exemplary embodiment, the system 330 is designed and operated to minimize the friction between the expansion device 12 and the tubular member 16.

[00101] Although illustrative embodiments of the invention have been shown and described, a wide range of modification, changes and substitution is contemplated in the foregoing disclosure. Accordingly, it is appropriate that the appended claims be construed broadly.

## CLAIMS

1. An expansion cone for radially expanding multiple tubular members comprising:  
a body having an annular outer peripheral surface; and  
at least a portion of the surface being textured with friction reducing reliefs recessed into the surface,  
wherein the surface comprises a laser dimpled surface;
2. The expansion cone as defined in claim 1, wherein the multiple tubular members comprise multiple pipeline members.
3. The expansion cone as defined in claim 1, wherein the friction reducing reliefs are concentrated at a leading edge and a trailing edge of the outer peripheral surface.
4. A method for radially expanding a tubular member comprising:  
providing a tubular member having an inside diameter;  
providing an expansion cone having an annular outer peripheral surface comprising a diameter greater than the inside diameter of the tubular member;  
texturing the outer peripheral surface with friction reducing reliefs recessed into the surface; and  
moving the expansion cone axially through the tubular member for radially expanding and plastically deforming the tubular member,  
wherein the surface comprises a laser dimpled surface;
5. The method as defined in claim 4, wherein the tubular member comprises a pipeline member;
6. The method as defined in claim 4, wherein the friction reducing reliefs are concentrated at a leading edge and a trailing edge of the outer peripheral surface.
7. A reduced friction radial expansion apparatus comprising:  
a plurality of tubular members having an axial passage formed therethrough comprising an inside diameter;  
an expansion cone having an annular outer peripheral surface comprising an

outside diameter greater than the inside diameter of the axial passage; and  
at least a portion of the outer peripheral surface being textured with friction  
reducing reliefs recessed into the surface,  
wherein the surface comprises a laser dimpled surface.

8. The apparatus as defined in claim 7 wherein a low friction material is deposited in the reliefs.
9. The apparatus as defined in claim 7 wherein the outer peripheral surface comprises a flush surface comprising a combination of portions of material of the expansion cone and portions of a low friction material deposited in the reliefs.
10. The apparatus as defined in claim 7, wherein the plurality of tubular members comprises a plurality of pipeline members.
11. The apparatus as defined in claim 7, wherein the friction reducing reliefs are concentrated at a leading edge and a trailing edge of the outer peripheral surface.

